Safety Assessment and Up-grades Executed and Proposed at Dhruva Reactor Following the Accident at Fukushima Daiichi Nuclear Power Plant

C.G. Karhadkar
Bhabha Atomic Research Centre, Mumbai-400085, India
E-mail: karhadka@ barc.gov.in

Abstract: Dhruva is a 100 MW research reactor, fuelled with natural uranium and cooled and moderated with heavy water. It is located in Bhabha Atomic Research Centre, Mumbai. It was commissioned in 1985. Following the Fukushima Daiichi nuclear accident, a complete review of existing system configuration was undertaken to ascertain reactor's capabilities to withstand extreme natural event, like earthquakes, tsunamis, storm surges etc. Various safety up-grades have been undertaken or are proposed to be executed in order to address issues that have surfaced. Several measures for improving safety margins against BDBEs, have been taken.

Key Words: Fukushima, Dhruva, Extreme natural events, reactor safety

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I. Introduction:

Fukushima Daiichi was an extreme event, where, "Station Blackout" "Beyond Design basis Seismic Event" and "Beyond Design basis Flood" occurred simultaneously. Considering the severity of the situation at Fukushima which lead to loss of operational and safety systems, a comprehensive review of existing system configuration of Dhruva reactor was undertaken to ascertain it's capabilities to withstand extreme natural events. Various safety up-grades have been undertaken or are proposed to be executed in order to address issues which have surfaced to improving safety margins against BDBEs (Beyond Design Basis Events).

II. Post Fukushima review of external events:

A. Review Methodology:

External Flooding: The grade level for recent nuclear facilities is decided based on the combinations of phenomena that can maximize flood water level at the facility. These are decided based on guidelines given in AERB (Atomic Energy Regulatory Board) safety guides, AERB/SG/S-6A and AERB/SG/S-6B for inland and coastal sites respectively. Adequacy of flood protection aspects of older plants like Dhruva form part of Periodic Safety Reviews (PSR), which was concluded in 2014 as part of its relicensing. For coastal sites like Dhruva, estimation of maximum water level is based on summation of astronomical high tide and wave height either due to storm or tsunami and their respective wave run-up to arrive at the most conservative estimate of flood level. Other than this, Probable Maximum Flood (PMF) due to Probable Maximum Precipitation (PMP) is also considered. The grade level of the site is decided based on maximum water level due to above conditions. If site cannot be graded to this level, suitable engineering measures are designed so that the water level does not jeopardize safety of the facility.

Design basis for Safe Shutdown Earthquake (SSE): Assessment of seismicity and related hazards constitute a major part of the siting criteria for recent nuclear facilities and PSR for older facilities. A site is deemed unacceptable, if a nuclear facility is proposed in seismic zone V, as per the seismic design code published by the Bureau of Indian Standards (IS: 1893-2002) or it is prone to ground failure phenomena during seismic events or if there is an evidence of a seismic capable fault within 5 km of a site. For estimation of ground motion corresponding to Safe Shutdown Earthquake (SSE) level, the probable maximum earthquake potential of each seismogenic source (fault) is estimated taking into account the maximized value of historical/recorded seismicity attributable to the fault. The source point of this maximized earthquake on the fault is brought nearest to the site. For this magnitude and distance combination, earthquake acceleration is determined. The exercise is repeated for all faults surrounding the site and the maximum of accelerations thus derived is adopted as design basis SSE level acceleration. The spectral shape is derived conservatively considering an ensemble of past earthquake records on geo-seismically similar regions and local site soil/rock conditions as per AERB guide AERB/SG/S-11 (1990). The design basis vibratory ground motion, is also probabilistically derived for Operating Basis Earthquake (OBE) and SSE level. SSE represents the maximum potential vibratory ground motion that can be expected for the region with Mean Return Interval (MRI) $\geq$ 10,000 years and OBE, with MRI ~100 years. Higher of the two (i.e. deterministic and probabilistic value) is adopted for a site.

B. **Assessment of threat:**

Tsunami: The submarine faults capable of generating tsunamis are located at very large distances, of more than 800 km from the Indian coast. Thus, unlike in Fukushima, the possibility of simultaneous occurrence of an earthquake and a tsunami at Indian coastal nuclear installations is almost non-existent. Makran subduction zone in the southern Pakistan is seismically active. There have been several historical tsunamigenic earthquakes from this region, viz. in 1765, 24th Jan 1851 and 27th Nov 1945. During 1945 activity, Mumbai was hit by tsunami waves. In all coastal nuclear installations, tsunami early warning system is made operational. During the Sumatra earthquake event of April 11, 2012, Indian National Centre for Ocean Information Services (INCOIS) Hyderabad issued its first bulletin within eight minutes ie.1416 hours IST. This earthquake with magnitude 8.5 had the capability to generate a tsunami. Post 2004 Indian Ocean Tsunami, Tsunami hazard assessment with mathematical tools complimented by local bathymetry data was carried out. Analysis was completed for all coastal stations. Analytical computer codes used were validated against 2004 tsunami observed water levels and through benchmarking. A national level round robin exercise to validate the computer code against 2004 tsunami was carried out. For western coast Tsunami analysis for the Makran fault was carried out, after considering earth quake of 8.2 magnitude on Richter scale, which occurred in 1945. Further sensitivity analysis was also carried out up to a 9.0 magnitude earthquake. Based on the analysis it is concluded that, for costal sites on the west coast, where Dhruva reactor is located, extent of flooding due to tsunami is well below the present Design Basis Flood Level (DBFL). Tsunami due to this fault will arrive at Mumbai after a delay of 270 minutes and the maximum height predicted is 1.05

meters including wave run up. Presence of mangroves around the coast line of BARC, provide a natural protection against Tsunami.

Intense precipitation: Consequent to flooding in Mumbai, on 26th July 2005, when 944 mm of rainfall took place in 24 hrs, an exhaustive study to assess the flood hazard due to storm surge/ intense precipitation was carried out by Central Water & Power Research Station (CWPRS) Khadagwasla, Pune. The Probable Maximum Precipitation (PMP) rate at the site was revised from 100 mm/hr to 203 mm/hr; accordingly various drainage systems have been up-graded to cater to this requirement.

Storm Surge hazard for coastal sites: Storm wave hind casting and storm surge analysis for Mumbai coast was carried out. Storm tracks and synoptic charts for 115 years (1891-2005), passing by the coast near Mumbai, from India Meteorological Department (IMD) were utilized for storm wave and storm surge hind casting. Extreme value analysis of hind cast storm wave data was carried out to determine the wave conditions with different return periods at Mumbai coast at water depth of 30 m. Wave transformation studies were carried out and design wave height at Mumbai coast at the water depth was determined for different return periods. Similarly, extreme value analysis of hind cast storm surge data was also carried out for different return periods. The greater height of these two analyses, corresponding to return period of 1000 years was adopted. As the predicted storm surge is higher than tsunami, same was adopted as DBFL for Dhruva.

Seismic Event: For Dhruva SSE value for a design basis seismic event is set at 0.2 g and OBE at 0.1g.

C. **Guide lines for Beyond Design Basis Events:**

Interim guidelines, for quantification of beyond design basis flood level for safety margin assessment of nuclear facilities, as issued by AERB are as follows:

Beyond design basis flood for coastal sites: Considering available data for past storms, it was recommended that a pressure drop of 100 mbar, associated wind speed of 300 kmph for east coast and 240 kmph for west coast and a radius of 50 km would be taken as an upper bound value for the postulated beyond design basis cyclonic storm. The translational speed of storm is suggested as 40 kmph. The total height of the wave shall be summation of (i) Maximum tide height, (ii) Storm surge height, (iii) Wave set up and (iv) Wind induced wave run-up. Adding all the factors CWPRS suggested the BDBF level to be 3.5 meters above the maximum high tide. This is significantly higher than the grade level for Dhruva reactor and beyond a level of cliff edge effect.

For assessment of extreme tsunami event, all physically possible combinations and variations of tsunamigenic source parameters and accurate near shore data including the effect of built environment around the site, were suggested. It was also suggested to use a validated model considering all possible combinations of causative phenomena in the detailed site specific analyses to estimate flood water levels. This analysis was already carried out as part of the round robin exercise and it is concluded that it is not likely to affect Dhruva reactor.

Beyond design basis earthquake: Recent occurrence of earthquake events like Niigataken Chuetsu-oki Earthquake in 2007 and the Great East Japan Earthquake in 2011, have indicated the possibility of NPPs being subjected to ground motions beyond their design values. In recent times peninsular India also experienced earthquakes larger than the regional estimates of the maximum magnitude e.g. Koyna earthquake of 1967 of 6.5 magnitude, and Latur earthquake of 1993 of 6.2 magnitude.

One suitable approach to evaluate the capability of the nuclear facilities to withstand ground motion beyond the design values is the estimation of seismic margins utilizing as-built information. Work had already been initiated in this regard. Older generation plants like Dhruva were seismically designed following the standards prevailing at the time of their construction, but not with the rigor of the current design practice. These plants are being seismically re-evaluated following the methodologies as suggested in the IAEA Safety Series-28 for assessing the margins.

III. Present configuration of important safety/safety related systems of Dhruva:

Dhruva reactor systems were reviewed for their sustainability and functionality in event of Beyond Design Basis Events such as earthquake or flooding with respect to, (i) Shut down capability and guaranteed shutdown. (ii) Decay heat removal and power supply system. (iii) Containment integrity and controlled venting of containment. (iv) Cooling and submergence of stored irradiated fuel assemblies in storage bays.

Brief Description of the reactor safety/safety related systems:

1. **Shut down system:** Fast acting shut-down system consists of a set of spring accelerated gravity driven (fail safe) fast acting, nine air-cooled cadmium shut-off rods of annular design arranged in two banks. They provide a minimum sub-criticality of 90 mK. Other than this, gravity assisted dumping of moderator in the reactor vessel to a dump tank is also provided to achieve long-term shut-down safety with the help of 6 number of spring to open (fail safe), quick opening control and dump valves. They provide a minimum sub-criticality of 50 mK. Both the systems are gravity assisted and fail safe in nature. Hence it will be possible to shut down and maintain the reactor in shut down state even during BDBEs.

2. Decay Heat Removal and Power Supply System:

Decay Heat Removal System: Three primary coolant loops, each consisting of a Main Coolant Pump (MCP, 540 kW), a heat exchanger and associated valves and piping (all of SS-304L Grade), are provided to remove the heat generated in the core. Each loop is also equipped with a smaller capacity Auxiliary Coolant Pump (ACP, 10 kW) for decay heat removal. ACPs are provided with two prime-movers; a water turbine and an electric motor fed from uninterrupted class-II power supply. A common shaft from turbine and motor with freewheel coupling in between connects to ACP pump shaft and provides the motive power for the pump. Emergency Cooling Water (ECW) flowing under gravity from OHST (Over Head Storage Tank, having 1800 $m^3$of inventory) provides the motive power to run ACP turbine. Barring first 15 minutes, one auxiliary pump and one turbine equivalent secondary flow is adequate for core cooling. On start command, ECW flow to turbine is set in by opening of spring to open (fail safe design) control valves provided in the circuit. This water from turbine outlet then passes through the secondary side of primary heat exchangers removing the decay heat, before joining underground dump tank (UGDT). Inventory in OHST can provide power water for primary cooling and secondary cooling for a period of 8.0 hours without any makeup. The collected water inventory in UGDT is pumped back to OHST through flooded suction make-up pumps (two numbers) driven by 55 kW motor provided with redundant Class-III power supply. (From main DG sets as well as off line Station Black Out DG sets). Provision also exists to supply ECW flow directly to ACP turbine by operating OHST make up pump in dump tank-to-dump tank recirculation mode. Various commissioning tests have proven that evaporative losses from OHST & UGDT and heat losses from the piping acts as an ultimate heat sink.

Class IV supply: Electrical power supply to Dhruva 22 kV sub-station, is fed from 110 kV substation, through two physically separated underground 22 kV feeders. Each feeder individually has adequate capacity to meet the maximum power demand of the reactor. Electrical Power supply to site from the grid is provided through 4 feeders. Two of these feeders are overhead transmission line of 110 kV and the other two are underground feeders of 22 kV. Reactor trip is provided on Class IV power under voltage condition, persisting for more than 200 milliseconds.

Class III supply: On a Class IV failure, power is supplied by three diesel generators of 500 kVA capacity within ~ 35 seconds. Adequate inventory of diesel is always maintained to run diesel generator sets to supply class-III power to safety systems in case of class-IV power failure. Two main diesel storage tanks, each of 20,000 liter capacity and 1000 liter capacity individual DG day tanks are provided for the same. Minimum inventory of 23,000 liters of Diesel oil is always maintained in the diesel storage tanks. This quantity is sufficient to run all the three main DG sets for 2 days and subsequently one of the DG sets for another 5 days to meet Class-III power supply demand in the event of prolonged Class IV power outage.
In addition to this, two numbers of dedicated Station Black Out (SBO) DG sets are provided exclusively for operation of Over Head Storage Tank (OHST) makeup pumps. Operation of these pumps alone can ensure core cooling on primary, secondary as well as transportation of heat to ultimate heat sink. These DG sets are kept isolated from the class -III system and are connected manually on demand. Other than this, there are two portable diesel engine driven pumps provided for makeup of the OHST from UGDT.

Class-II supply: Class II 415 V AC uninterrupted supply is provided by two numbers of 250 kVA Motor Alternator Sets and two numbers of 20 kVA inverter sets driven by Class I power supply.

Class-I Supply: 240 V DC and 48 V DC supply from Automatic Constant Voltage Rectifiers (ACVRs) driven by Class-III and backed up by respective battery banks of

1200 Amp-hour capacity and of 300 Amp-hour capacity form part of the class-I power supply. In case of prolonged station black out condition, only one of the two 250 kVA MA set can be operated with one shut down cooling pump on motor mode. In this case one battery bank can last up to 10 hours for load of 120 ampere. The total load on 48 V DC system is 30 ampere. There are two battery banks of 300 ampere-hour capacity to cater 48 V DC Class-I load. One battery bank can last up to 10 hours.

3. **Containment System:** The reactor block along with experimental facilities, heavy water system, vault and shield cooling systems, isotope handling facility etc. are housed in a low pressure reactor containment building which is a reinforced concrete structure. Provisions exist for automatic (fail safe) isolation of the containment from outside atmosphere and controlled depressurization of the containment by releasing air through HEPA and charcoal filters to the stack, through dampers which are fail safe to open and others which can be operated manually. Hence controlled venting of the reactor building through stack in any of the BDBEs is possible.

4. **Spent Fuel Storage Bay (SFSB):** Low density storage pool of 1000 m^3 water volume is provided for storage of spent fuel in the reactor. The tank is partly underground and partly over ground, it is SS lined with tell-tale device for identifying leakage if any. The water recirculation piping layout is such that fuel submergence/shielding is assured even with piping failure. With experience it is proven that separate cooling is not required for SFSB water, evaporative cooling from the pool is adequate.

A detailed analysis was carried out for assessing the fuel safety in SFSB following unloading of the core. It was seen that, for worst case of emergency un-loading of core at the fastest unloading rate and remaining positions already full with spent fuels, the maximum heat load works out to be 300 kW. For this condition without any external cooling, bay water temperature stabilizes at 70^{o}C after 15 days. SFSB has enough water inventory to keep fuel submerged for a period of 2 months. Adequate make up facility from redundant water sources like, OHST, service water and recently added fire hydrant lines is available. Hence for the worst scenario safety of fuel in SFSB is assured.

IV. Review of Dhruva SSCs with respect to BDBEs for Flooding & Seismic Event and changes in configuration executed / proposed.

1. **Seismic BDBEs:** A complete walk down of the reactor structures was taken, by civil and seismic experts. Health assessment of reactor structure using NDT techniques is in progress. Preliminary, assessment has indicated that there are no signs of distress on the structures. Seismic requalification of Dhruva reactor for assessing the margins beyond DBE as per the current standards with Trombay site (site specific) spectrum and soil characteristics is in progress. Results of the analysis completed so far have indicated that adequate margins (at least two times) are available for the SSCs. Hence it is expected that most of the structures and systems will be able to withstand the seismic loads and operation of safety / safety related system will not be affected. In case safety margins are observed to be less necessary retrofitting will be considered.

2. **BDBE due to Storm Surge:** Safety of Dhruva reactor has been well demonstrated up to its design basis flood level. Beyond this there will be a cliff edge effect and many of the systems will get affected viz. Class-III power sources (main and SBO), Class-II power sources and switch gear, OHST make up pumps, controls, instrumentation, communication, lighting etc. Equipment located at higher elevation and those inside reactor building will remain available viz. OHST, Class-III switch gear, Battery banks and their chargers, Shut down cooling pump motor/turbine sets, all the battery banks and class-I switchgear, Facility for venting of reactor building, Portable engine mounted pumps for making up OHST, Supplementary Control Room (SCR) etc.

Complete review was carried out to assess effect of such an overwhelming event on the reactor safety considering following inputs:

There are typically three stages of mitigation of an event like storm i.e. (a) **preparatory Stage**: As per the metrological expertise available in the country, it was felt that a pre-warning of about 72 hrs is possible for such an event. Hence, it was decided that a conservative response time of two days (48 hrs) can be assumed for making adequate preparations for fighting a BDBF. (b) **Fighting Stage**: From the literature survey, it is understood that a typical storm surge can last up to 24 hours with peak duration of 6 hour. Hence it was decided that a conservative mission time should be at least for two days (48 hrs) (c) **Restoration Stage**: It was felt that a time of about seven days would be adequate for minimal class IV power supply and makeup pump restoration.

Additional provisions made/ being proposed for mitigation of BDBE and rationale:
Based on the inputs, detailed mitigation plan was prepared and additional provisions have been made/ being made, based on issues that have surfaced, which are as follows:

Tripping of Reactor on a Seismic Event:
- Seismic trip on the reactor is being provided on 2 out of three logic using three free field sensors, if ground motion approaches 70-80% of OBE value. Additional four sensors will be provided for recording the time history and response spectrum at reactor building/ service building foundation and top of pile block and top of service building.

Provision of Emergency Power supply and distribution:
- All class-III buses and switchgear are located at higher elevation; they will be used to provide power supply in reactor building. Further distribution can be done by laying temporary cables (which have been kept ready and available) to various emergency equipment in reactor building.
- Plan for upgrading the existing 500 kVA DG sets with new 625 kVA DG sets was on the anvil. It was decided to construct a new seismically qualified building and provide two 625 kW air cooled DG set in this building at higher elevation with adequate diesel storage facility.
- For interim period a 200 kW portable DG set maintained by fire services station has been identified and ear marked for this purpose and which can be shifted to the site and placed at higher elevation, in short duration of time to provide emergency power to, OHST makeup pumps from flood proof pump house, Shut down cooling pump motors,

few dewatering pumps, small capacity air compressor to keep the air locks closed, Other emergency loads such as charging of battery banks, instrumentation in Supplementary Control room (SCR), communication system, emergency lighting (arrangements are also being made for providing solar lighting).

- Battery banks #1, 2, 3 and 4 can provide uninterrupted power to lighting loads, communication facility for few of the identified control stations, Control and instrumentation in SCR. It is proposed to transfer one inverter at higher elevation for making available uninterrupted AC power for operating one shut down cooling pump through class-III switch gear.

Provision of Power water and OHST makeup:

- Additional pump house, having two make up pumps with independent OHST make up line, was being built for the problem of internal flooding. This pump house has also been made external flood proof, up to BDBFL.
- Additional make up line to OHST through an independent pump house has been provided. Also the OHST overflow line was modified to provide an external hookup point to make up OHST through this line, using any external source.
- Modifications are being carried out to provide direct hookup points in loop#1 turbine inlet and outlet lines and primary heat exchanger for driving one turbine and providing secondary cooling, using any water source (like fire hydrant water).
- Additional hookup point to provide high pressure water source, for directly driving the turbines and providing secondary cooling, external to the reactor building has been made.

Monitoring of important parameters:

- Monitoring of plant parameters, including necessary information pertaining to neutronic power, status of shut-down devices (shut-off rods, dump valves & control valves), moderator level, Shut down cooling pump status, core gross flow, each loop flow, primary coolant inlet temperature, reactor building pressure & ventilation gamma are provided in SCR, which will remain available. It is ensured that, all the sensors and junction boxes connected to the SCR will remain above BDBF.

Estimation of time to initiate secondary cooling after 48 hours of Shut Down:

- Time available with primary circulation on, without secondary cooling was evaluated giving credit to stagnant water inventory in Vault and primary heat exchangers. It is noted that after 48 hours, of reactor shut down, time available before reactor coolant temperature reaches 70^{o}C (with in the design limits), will be about 16.0 hours.

V. Conclusion:

Considering various improvements made/ proposed in the system configuration, it is felt that it will be possible to cope with an overwhelming beyond design basis natural event as described above.

Reference:

[1] National Report to the Convention on Nuclear Safety (August 2012)
[2] Nuclear Engineering and Design India's Reactors: Past, Present, Future Volume 236, Issues 7-8, Pages 681-930 (April 2006).